Hydraulic analyses for assessing the ecological Reserve for rivers in South Africa

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Abstract

Water resources in South Africa are limited and their management and protection is critically important for the sustainable economic and social development of the country. Over the last decade, much effort has been devoted to developing policies, structures and methodologies for the management and protection of South African water resources. The National Water Act (No. 36 of 1998) (NWA) has been formulated to provide a fundamental reform of the law relating to water resources. Implementation of the NWA requires that an ecological Reserve be determined for all significant resources. Determination of the ecological Reserve is a complex procedure involving a wide range of disciplines, including, aquatic and social scientists, hydrologists, geomorphologists, hydraulicians, engineers and resource economists. The ecological Reserve focuses on the amount and quality of water required to maintain a river ecosystem and related habitats in a particular ecological state. Hydraulic habitats can be characterized by flow velocity, flow depth, nature of substrate, and to some extent by inundated area. The link between hydraulic habitat and stream flow is found through hydraulic river modelling. In Reserve studies considerable attention is focussed on the low-flow condition, and sites are often characterised by large-scale roughness where the flow depth and the height of the substrate elements are of the same order of magnitude. Successful prediction of the flow velocity and the flow depth under such conditions depends on general understanding of the nature of the flow resistance, and application of appropriate approaches for its prediction. Recent developments of hydraulics for assessing ecological Reserves for rivers in South Africa are discussed.

Keywords: *hydraulic modelling, flow resistance, biota habitats.*

1 Introduction

Water resources in South Africa are limited and their management and protection is critically important for the sustainable economic and social development of the country. Over the last decade, much effort has been devoted to developing policies, structures and methodologies for the management and protection of South African water resources. A variety of new policies, approaches and procedures such as the National Water Act, the National Environmental Management Act, the Water Law Principels, the Environmental Conservation Act, and the Integrated Environmental Management procedure have been developed to provide the strategies and guidelines for management of water resources in South Africa.

The National Water Act (No. 36 of 1998) (NWA) has been formulated to provide a fundamental reform of the law relating to water resources management in an integrated manner. The NWA views the river as a "resource" rather than a "user" of water. The term resource "*is used to include the health of all parts of the water resources, which together make up an ecosystem, including plant and animal communities and their habitats*" (DWAF, 1997; DWAF, 1998). Sustainability and equity are identified as central guiding principles of the Act in the protection, use, development, conservation, management and control of water resources.

The NWA provides for rivers' ecological requirements to be founded on environmental flows, which will maintain ecological structure and function, channel, bed and floodplain form, function and connectivity, and a measure of its natural flow characteristics. Implementation of the NWA requires that an ecological Reserve be determined for all significant resources.

Ecological Reserve determination is an estimation of the flow requirements of different components of a river. It focuses on the amount of water required to maintain the system in a particular ecological condition. The estimation of flow required for different aquatic components is a complex procedure, and a generic Resource Directed Measures (RDM) methodology for protection of water resources was developed, as described in Water Resources Protection Policy Implementation: Resource Directed Measures for Protection of Water Resources (DWAF, 1999).

The level of detail or intensity of RDM determination is closely related to the ecological importance and sensitivity of the water resource, the scale and degree of the impact of proposed water use, and the urgency of the Reserve determination.

There are four levels of RDM determination: Desktop, Rapid, Intermediate and Comprehensive. The desktop determination is a quick, often very low confidence assessment proposed for use in the National Water Balance Model. For the desktop estimation a local desktop reserve model for an initial low confidence estimate of the quantity component of the Reserve for rivers was therefore developed (Hughes and Hannart, 2003).

There are 3 levels of rapid determination. Level 1 is a low confidence estimation using the desktop model, with field assessment of present ecological status (proposed for use in unstressed catchments of low ecological importance and sensitivity). Level 2 involves the biotic surveys with only a measurement of discharge, while level 3 involves hydraulic field work and modelling, and fish and invertebrate surveys. The intermediate determination is a medium confidence assessment that was proposed for use in relatively unstressed catchments. The intermediate assessment involves hydraulic modelling based on two or three observations over a range of flows, hydrological modelling, and fish and invertebrates surveys. A higher level of confidence is provided by the comprehensive assessment, where extensive field data should be collected and used by specialists for the quantification of the Reserve. The approach is proposed to be applied for very ecologically important and/or sensitive catchments (the size of the river/reach as well as the type and extent of water resource development are important considerations.)

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2 Ecological Reserve Determination

Understanding of ecological flow requirements of river ecosystems and applications of appropriate methodologies are essential parts of the determination of the ecological Reserve process. The development and application of methods and techniques for prescribing the ecological flow requirements started in the 1950s, and since then many different types of methodologies and approaches have been proposed (King and Tharme, 1994). In general, methodologies can be divided into four basic categories (Tharme, 2002): methodologies based on historical flow records, methodologies based on the relationship between physical habitat and discharge, methodologies based on the instream habitat simulation methods (with habitat defined in terms of the requirements of a particular target species), and holistic methodologies and alternative approaches to instream flow assessment.

In South Africa, activities addressing the influence of modified flow regimes on riverine ecosystems were initiated in 1987, the needs for the methods for assessing the ecological flow requirements of rivers were recognised, and development of local methods to provide guidance on the sustainable use of rivers' water-resources started in 1989 (King and Tharme, 1994). The development of methods for assessing the ecological consequences of managed flow regimes resulted in development of three South African methodologies: Building Block Methodology (BBM) (Tharme and King, 1998), Downstream Response to Imposed Flow Transformations (DRIFT) (Brown and King, 2000) and the Flow Stressor-Response (FS-R) (O'Keeffe and Hughes, 2004). The application of BBM, DRIFT and FSR for ecological flow determination requires flow requirements to be expressed as discharge rates through assessments of the presence of suitable habitat for certain biota at different flows. Biota do not respond to discharge directly, but rather to the hydraulic habitats determined by local hydraulics, in other words by hydraulic characteristics such as flow depth and flow velocity. Specification of species habitat requirement in terms of hydraulic variables is therefore essential.

3 Defining Hydraulic Parameters for Fish and Macroinvertebrates Habitats

Flow is strongly correlated with the most important physicochemical factors in an ecosystem, which in turn, influence species richness, population dynamics, resilience and abundance (Poff and Ward, 1990). Ecological Reserve determination requires estimation of flows that will satisfy biota habitats. According to the American Fisheries Society, "habitat" is defined as the "specific type of place within an ecosystem occupied by an organism, population or community that contains both living and nonliving components with specific biological, chemical, and physical characteristics including the basic life requirements of food, water, and cover or shelter". Aquatic habitat can be characterized in kind by the flow velocity, flow depth, nature of substrate and degree of cover, and in extent by inundated area. Cover is not a hydraulic characteristic, and the substrate is not directly a hydraulic characteristic, but is determined by the prevailing hydraulics. Description of biota habitats in terms of hydraulics is therefore required.

3.1 Fish Habitats

Kleynhans (1999) suggested that the hydraulic information necessary to characterize habitat for fish is depth-averaged velocity (V) and flow depth (D). Together with substrate and vegetation cover information, these are sufficient to broadly describe fish habitat. Further, he suggested that velocity and depth need only be specified coarsely, and has proposed the following four velocity-depth classes (hydraulic habitat types), as adapted from Oswood and Barber (1982):

- *Slow (<0.3 m/s) and shallow (<0.5 m)*: This includes shallow pools and backwaters.
- *Slow (<0.3 m/s) and deep (>0.5m)*: This includes deep pools and backwaters.
- *Fast (>0.3 m/s) and shallow (<0.3 m)*: Shallow runs, rapids and riffles fall in this class
- *Fast (>0.3 m/s) and deep (>0.3 m)*: Deep runs, rapids and riffles fall under this class.

For each velocity-depth class, the presence of features that provide cover for fish (i.e. refuge from high velocity, predators, high temperatures, etc.) are also taken into consideration (Kleynhans, 1999). These features include:

- *Overhanging vegetation*: thick vegetation overhanging water by approximately 0.3 m and not more than 0.1 m above the water surface. This includes marginal vegetation.
- *Undercut banks and root wads*: banks overhanging water by approximately 0.3 m and not more than 0.1 m above the water surface.
- *Stream substrate*: various substrate components (rocks, boulders, cobbles, gravel, sand, fine sediment and woody debris "snags") that provide cover for fish.
- *Aquatic macrophytes*: submerged and emergent water plants.
- *Water column*: used to assess depth in relation to the size of fish.

Irrespective of the ecological flow method applied, holistic methods require an assessment of the suitability of different hydraulic characteristics for biota over a range of discharges. The velocity-depth descriptions and associated substrate and cover features provide a broad categorisation of hydraulic habitats for fish. The presence of these hydraulic habitat types may be quantified using a relative abundance scale with associated proportional percentage occurrence, an example of which is given in Table 1 (adapted from Rankin, 1995).

Table 1: Abundance scoring of habitat types for fish or macroinvertebrates.

Descriptor	Score	Occurrence (%)
None	0	0
Rare	1	0-5
Sparse	2	5-25
Moderate	3	25-75
Abundant	4	75-90
Very abundant	5	90-100

3.2 Macroinvertebrate Habitats

The main parameter used in the classification of macroinvertebrate hydraulic habitat is depth-averaged velocity. This, together with substrate type and vegetation, may be used to broadly describe macroinvertebrate habitat. Two of the proposed habitat type definitions are modifications of the well-known macroinvertebrate-based biotope classifications: "Stones in Current" (SIC) and "Stones out of Current" (SOC). These definitions originate from the SASS (South African Scoring System) index for broadly assessing river condition on the basis of the sensitivity of macroinvertebrate families present at a site. These biotope definitions are not particularly meaningful from hydraulics (i.e. use of the term "current") or geomorphological (i.e. use of the word "stones") perspectives, and have therefore been modified (Jordanova et al, 2004). The proposed five habitat type classifications are:

- *SCS: Slow (< 0.3 m/s) flow over/around Coarse Sediments (size > 16mm) and bedrock*
- *FCS: Fast (> 0.3 m/s) flow over/around Coarse Sediments (size > 16 mm) and bedrock*

The SIC and SOC substrate classifications have been modified to include substrates other than gravels (equivalent of "stones" in the original biotope classification), although it is recognised that large gravel and loose cobbles generally provide better substrate habitat than boulders and bedrock for rheophilic taxa. Un-embedded sediments with interstitial spaces also provide superior quality habitat than embedded sediments. The quality of substrate provided by submerged and emergent (partially submerged) coarse sediments also differs, and relative flow depth therefore needs to be taken into account when evaluating the suitability of these two habitat types.

- *SV: Slow (< 0.3 m/s) flow through Vegetation*
- *FV: Fast (> 0.3 m/s) flow through Vegetation*

These two habitat types include both fringing and aquatic vegetation. Leafy vegetation is recognised as providing more suitable habitat for vegetation-dwelling taxa than, for example, sedges or reed stems.

- *SFS: Slow (< 0.3 m/s) flow over Fine Sediments (size < 16mm)*

This habitat type includes sediments ranging from clays and silt to gravels. The abrasive action of mobile sediments (particularly sand) reduces the quality of this habitat type for target macroinvertebrate taxa.

The presence of these habitat types for macroinvertebrate fauna may be rated using the relative abundance scoring system developed for fish (Table 1). These "presence" ratings also account for the suitability (or quality) of each of these broadly defined classes, by incorporating additional considerations.

From above it can be seen that the velocity-depth distributions and associated substrate and cover features provide habitat for aquatic animals. Prediction of these hydraulic parameters is critical for establishing the ecological flow requirements for fish and macroinvetebrates in Reserve determinations.

4 Hydraulics for Reserve Determination

4.1 One-dimensional Hydraulic analyses

The primary product of hydraulic analyses are relationships between discharge and the following determinants, which have been found over the course of numerous flow assessments, to be the most useful: depth (maximum and average), velocity (average), wetted perimeter, and width of the water surface. The discharge-depth (or rating) relationship is fundamental to hydraulic analysis, and is generally derived from a combination of measured and synthesized data (Rowlston et al, 2000 and Birkhead, 2002). In order to develop stage-discharge relationships, two to three observations over a range of flows are needed. After obtaining observed data, hydraulic modelling of rating relationship for flows higher and lower than the observed is required (Figure 1). Modelling of stage-discharge relationship beyond the range of observed data required extrapolation of resistance coefficients. The validity of the extrapolation can be assessed by computing inferred resistance coefficients beyond the range of observed data, and comparing these with reasonable values based on the literature (e.g. Barnes, 1967; Hicks and Mason, 1998).

The next step is to fit recorded and modelled rating data to a relationship of the form given by Birkhead and James (1998)

$$y = aQ^b + c \qquad 1$$

where y is the maximum flow depth (m), Q is the discharge rate (m^3/s), and a, b and c are regression coefficients.

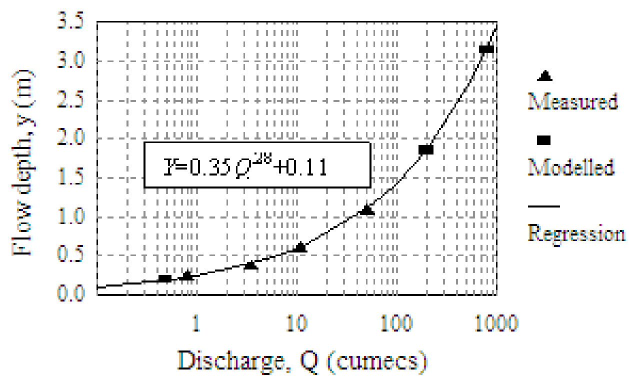

Figure 1. Example plot of a rating relationship on semi-log scale showing the observed and modelled data (Jordanova et al, 2004).

Once the rating relationship has been developed, it can be converted into relationships between flow rate and the biologically useful hydraulic parameters such as velocity, flow area and wetted perimeter.

The rating data and relationships between flow rate and velocity, flow area and wetted perimeter comprise the “standard hydraulic data” that are used in Reserve determinations in South Africa at the Rapid, Intermediate and Comprehensive levels. From a hydraulics perspective, the main difference between these three levels of Reserve assessment lies in the quantity of rating data that are measured at river sites: one, two and four data sets are generally collected for Rapid, Intermediate, and Comprehensive assessments, respectively. The proportion of measured and synthesized rating data (Fig. 1) determines the confidence in the fitted rating function and resulting hydraulic characterisation. For Intermediate and Comprehensive assessments, there may also be opportunities to survey and rate multiple cross-sectional profiles through different morphological features (ie. rapids/riffles, runs and pools).

In Reserve determination studies considerable attention is focussed on the low-flow component of the hydrological regime. Hydraulics under low flow (where the flow depth and the height of the substrate elements are of the same order of magnitude) is known as conditions of large-scale roughness. Successful prediction of flow resistance of the large-scale roughness depends on general understanding of the nature of the flow resistance, and application of the appropriate approaches for its prediction.

4.1.1 Flow Resistance

Flow resistance is a term used to describe the net effect of the forces driving and resisting the water movement, and is commonly represented by the ratio of the bed shear velocity to the mean flow velocity. When the flow depth, y, is four or more times the height of the bed material, h, the flow resistance can be considered to result from friction of the material forming the surface of the boundary, and can be described by well known friction coefficients such as the Chézy C, Manning’s n and the Darcy-Weisbach f: All of these account for the resistance processes with a single coefficient of resistance.

$$(V/V* = (8/f) = (C^2/g) = R^{1/3}/(gn^2) \qquad 2$$

Theoretical aspects of open channel flow resistance are documented in some publications such as Leopold et al (1960), Rouse (1965), Bathurst (1982), and Yen (2002).

Flow resistance has been studied by many researchers due to its importance in practical applications (e.g. Bathurst, 2002; Griffiths, 1981; Jarrett, 1984; Thorne and Zevenbergen, 1985; Lawrence, 1997; Smart et al, 2002). Three (large, intermediate, and small) roughness scales have been recognised (Bayazit, 1975; Bathurst, 1978). Furthermore, components of flow resistance as well as physical variables contributing to overall flow resistance have been documented (Bathurst, 1978, 1982; Bray and Davar, 1987; Lawrence, 1997, 2000). Various equations and resistance coefficients related to large-scale roughness have been developed (e.g. Jonker et al, 2001; Nikora et al, 2001). Some of them are very complicated and require comprehensive field data (Bathurst, 1978), while others are based on the relative submergence and require consideration only of the bed grain roughness (Bathurst, 2002; Jonker, 2001). Different modifications of resistance coefficients Manning's *n*, the Chézy *C* and the Darsy-Weisbach *f*, for application to appropriate conditions have been proposed.

When the channel bed material is large relative to the water depth, the flow resistance is exerted by the roughness elements' drag rather than boundary shear, and the resistance equations developed for estimation of small-scale roughness resistance are then not applicable. A different type of equation for prediction of the flow velocity, V has therefore been proposed (James et al, 2001; Jordanova et al, 2004), i.e.

$$V = \frac{1}{F}\sqrt{S} \qquad 3$$

with

$$F = \frac{1}{\sqrt{\dfrac{2g}{C_d nD}(A_t - n\ A_b)}} \qquad 4$$

in which S is the channel slope, g is gravitational acceleration, C_d is the roughness element drag coefficient, n is the number of roughness elements, D is the roughness element diameter, A_t is the considered bed area and A_b is the base bed area of individual roughness element.

Because the drag coefficient C_d depends on a number of variables, such as the Froude number, the Reynolds number, the roughness element shape and the relative depth, its estimation is not a simple procedure (Flammer et al, 1970). The experimental data were therefore used for development of a direct empirical formulation for the resistance coefficient F that does not include the drag coefficient C_d, i.e.

$$F = \left(\frac{W_{re}}{W_t}\right)^{0.255}\left(\frac{A_p}{A_b}\right)^{-0.465}\left(\frac{WS_{re}}{A_t}\right)^{0.374} \qquad 6$$

in which W_{re} is the volume of roughness elements within the considered flow element, W_t is the volume of the considered element, A_p is the projected cross-sectional area of the individual roughness element, A_b is the base bed area of the individual roughness element, WS_{re} is the wetted surface of roughness elements within the considered element, and A_t is the considered bed area. These equations were applied to the experimental data and results showed good agreement.

The roughness is of intermediate-scale if the relative submergence (the ratio of flow depth to roughness element height) lies between one and four. This regime represents a state of flow in which the surface roughness, as well as the frictional resistance, contributes to overall flow resistance, and the following equation for prediction of the flow velocity is proposed.

$$V = a\,\frac{1}{F}\sqrt{S} + (1-a)\frac{1}{n}R^{2/3}\sqrt{S} \qquad 7$$

where n is Manning's resistance coefficient, and R is the hydraulic radius, with

$$a = 1.125\left(\frac{y}{h}\right)^{-1.777} \qquad 8$$

4.1.2 Predicting Probability- Depth and Velocity Distributions

River biota (particularly fish and macroinvertebrates) display preferences for hydraulic habitats containing certain ranges of depth and velocity. The modelling of characteristics frequency-depth (Lamouroux, 1998) and frequency-velocity (Lamouroux et al, 1995) relationships is therefore valuable for providing typical spatial distributions, and these were adopted in South Africa.

4.1.2.1 Probability-Depth Distributions

Statistical analyses of the frequency-occurrence of flow depth along surveyed cross-sections provide measurement-based data on their spatial distribution. To describe typical variability in the distributions, surveys need to provide representative cross-sectional profiles through the different morphological features. Depth probability distributions for river reaches were modelled by Lamouroux (1998). The development was based on two data sets: the first included 104 distributions measured at various discharges in 22 different reaches in the Ruhr (Germany) and Bavarian River catchments; the second included 47 distributions measured for a range of discharges in 8 reaches of the Rhône and Ain Rivers in France. The reaches contained several pool-riffle sequences.

For a specified maximum depth and related discharge as determined from rating data, the actual depths along a cross-section are computed at equal distance increments. This is preferable to using actual surveyed elevations across the river bed, since these are usually measured at changes in slope and with a higher density of bed elevations in the low-flow channel. The range of depths (zero to maximum) along a cross-section/s is divided into equal depth class increments, and the frequency of occurrence within each depth class is computed. An example of plot of frequency-depth distributions along a rapid cross-section is given in Figure 2.

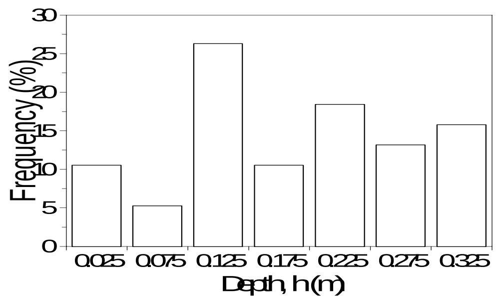

Figure 2. Example plot of frequency-depth distributions along rapid cross-section, for a discharge of 0.46 m^3/s and average and maximum depth 0.18 m and 0.35 m respectively. (Jordanova et al, 2004).

4.1.2.2 Predicting Probability-Velocity Distributions

Lamouroux *et al* (1995) developed a useful predictive model with distribution parameters that are related to descriptors of hydraulic variables in river reaches. The data used for model development were collected from 37 river reaches in France, with reach lengths ranging from 2 to 20 times the flow widths. Reaches were divided into between 3 and 17 longitudinal divisions, with each division further divided into transverse cells (from about 100 to several hundred cells). Depth averaged velocities were determined from point measurements at 20, 40 and 80% of the flow depth, measured from the bed. Point measurements were often found to deviate from theoretical logarithmic profiles (which assume resistance by boundary shear at the bed), since both emergent and submerged conditions were considered. The average dominant bed roughness was used, defined by the size of the roughness elements occupying the largest fraction of the bed. To allow valid statistical analyses, depth and roughness measurements were weighted using cell area (bed), and depth-averaged velocity was weighted using cell volume.

The measured frequency-velocity distributions varied from centred distributions with velocities grouped around average reach values, to decentred distributions with bi-modal velocity distributions. A probability density function was defined using a combination of a Gaussian distribution (centred), and Gaussian and exponential distributions (decentred).

An example of predicted probability-velocity distributions is plotted in Fig. 3 for discharge of 0.78 m^3/s.

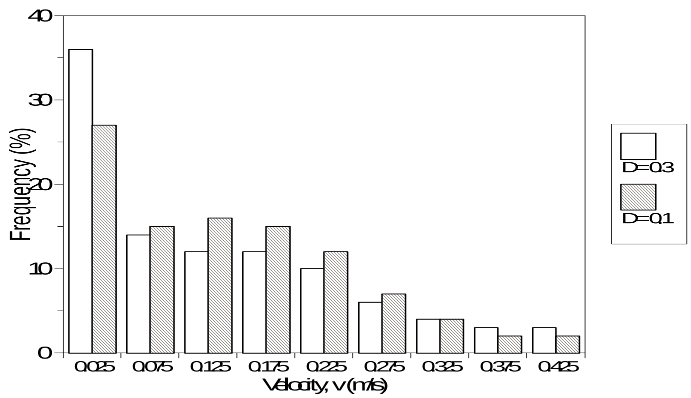

Figure 3. Example for modelled probability-velocity distributions for discharge of 0.78 m^3/s. The legend denotes mean roughness value (D) (Jordanova et al, 2004).

4.2 Modelling Approach

In Reserve studies considerable attention is focussed on the low-flow component of the hydrological regime, and sites are often characterised by large-scale roughness. This requires the analysis of shallow flows with complex boundaries (due to emergent bars and substrate elements), which produces numerical instabilities. Accurate modelling would require detailed topographic (including substrate) surveys and the use of a dense mesh, since flow through a number of adjacent nodes is required for stable numerical solutions. Furthermore, meshes may need to be re-constructed for different flows, due to changes in the position of boundaries and orientation of streamlines with changes in discharge. Kondolf *et al* (2000) maintains that highly accurate hydraulic modelling may be infeasible for rivers with complex channel geometry, and furthermore cannot resolve flow patterns at spatial scales at which fish often respond to the hydraulic environment. It was recognised that use of "standard hydraulic" approach in Reserve studies requires further development. A suite of three modelling tools has therefore been proposed for this purpose (Jordanova et al, 2004):

- QuickSurf
- RiverCAD
- HEC-RAS

4.2.1 Digital Terrain Modelling

Quicksurf is a general purpose surface modelling system running inside of FelixCAD. Quicksurf converts surface mapping data such as point and/or break-line data into contours, grids (GRDs), triangulated irregular networks (TINs), and triangulated grids (TGRDs).

4.2.2 Positioning and Extracting Cross-Sections from the Digital Terrain Model

RiverCAD is an advanced graphical modelling environment, providing support for the US Army Corps of Engineers one-dimensional flow analysis software HEC-RAS (Hydrological Engineering Centre - River Analysis System). River cross-sections may readily be extracted from the digital contour map developed using QuickSurf. RiverCAD incorporates a facility for mapping inundation as well as a raster image module for loading geo-referenced digital images.

RiverCAD provides the tools necessary for positioning and extracting cross-sections, measuring reach (channel and floodplain) distances between adjacent cross-sections, entering boundary conditions for steady-state hydraulic computations using HEC-RAS, and mapping flow inundation. Steady-state hydraulic computations can be performed within the RiverCAD modelling environment using the HECRAS version 2.0 module, whereas unsteady simulations require HEC-RAS version 3.0 or higher and HEC-RAS projects must be exported for this purpose.

4.2.3 One-Dimensional Hydraulic Modelling

HEC-RAS is an integrated system of software, designed for interactive use in a multi-tasking environment. The system comprises a graphical user interface, separate hydraulic analysis components, data storage and management capabilities, graphics and reporting facilities.

HEC-RAS allows for the incorporation of levees and ineffective flow areas to exclude flow areas from the analysis, and flow resistance. This allows modelled stages to better replicate measured values where a 1d analysis is used to simulate 2d conditions. Geometric data (cross-sectional profiles and reach lengths between them) form part of the RiverCAD analysis. Resistance coefficients (Manning's *n* is generally used), and the position of bank stations and ineffective flow areas, are adjusted as part of the flow calibration to achieve agreement between measured and modelled water surface profiles. HEC-RAS also provides the ability to specify flow-resistance factors that adjust flow resistance as a function of depth.

For steady-state analyses, boundary conditions are required at either the downstream, upstream or both boundary cross-sections, depending on whether flow is subcritical, supercritical or mixed, respectively. Boundary conditions take the form of measurement-based rating curves, derived from best-fit relationships between gauged discharge and observed stage levels. As for the single cross-section and rating curve approach, the hydraulic modelling of flows beyond the range of measured values relies on estimates of water surface gradient and flow resistance. Improved methods for the reliable prediction of these parameters for sites with large-scale roughness elements therefore remain a requirement.

4.3 Development of Hydraulic Software to Assist Reserve Determinations

The framework for the hydraulic Reserve model, HERR (Hydraulics for the Ecological Rivers Reserve), has been developed to address the following requirement:

- assist with the analysis of data, particularly for lower levels of determination where limited measured data are available (i.e. Rapid and Intermediate),
- streamline the presentation of results,
- provide greater conformity in the modelling approaches being used, and
- provide a system (data-base) for storing hydraulic information.

The model is coded in Delphi and is designed for integration with SPATSIM (SPatial And Time Series Information Modelling), which was developed at the Institute for Water Research, Rhodes University (Hughes, 2004). It consists of a main menu (*site, cross-section, analysis and view*), a description of the river and site names and cross-section number; tabulated cross-sectional data (which may be manipulated); hydraulic data including both recorded/measured (date, discharge, stage and slope) and calculated cross-sectional parameters (average velocity and maximum depth, and resistance coefficients according to Manning (n), Chezy (C) and Darcy-Weisbach (f); synthesized hydraulic data (for the purpose of extending measured rating values), which require estimates of the resistance coefficient and slope corresponding to a given specified maximum depth to compute discharge (as well as average velocity and stage).

The form also displays a plot of the cross-sectional profile used for viewing any measured or synthesized water level. The main geometric determinants (stage, maximum depth, perimeter and area) are listed alongside the cross-section. Additionally, the regression coefficients for a rating function given by the form of equation1 (Birkhead and James, 1998) are listed on the main form.

The software is being further developed to incorporate curve-fitting software to allow the regression coefficients in the rating function (equation 1) to be computed, providing a seamless hydraulic modelling environment. Provision is made for this application in the *analysis/rating* drop-down menu. The main menu items contain further drop-down menus. The drop-down menus under *site* include: *new, load from file, load from data-base save to file and save to data-base*. These allow a new site to be established and the data to be loaded from or saved to text files. The *cross-section* drop-down menu includes: *add* and *delete* for adding or deleting cross-sections to or from the site, and *add profile* for loading (and overwriting existing) cross-sectional profile data. The view menu includes the tasks: *cross-section* and *data-base*. The *view/cross-section* is based on a previous version of the hydraulic display software developed for the Lesotho-Highlands IFR in 1999, and displays water levels for up to six flows on the cross-sectional profiles. The hydraulic parameter values of the maximum and average depths, perimeter and average velocity are also listed. The remaining item on the *analysis* drop-down menu is *depth-frequency,* which launches the depth-frequency form given in Fig. 2.

5 Conclusions

To improve the use of hydraulics for ecological Reserve determination in South Africa the following conclusions and recommendations for further investigation can be made:

New resistance equations (7 and 8) distinguishing between large-scale and intermediate-scale roughness influences have been developed. General application of the proposed equations requires further investigation of:

- estimation of the large scale resistance coefficient F as a simple function of the bed material size characteristics, and
- further verification of the proposed coefficient, a, that effects partitioning of the influences of the large and small roughness scales on flow resistance.

The modelling of characteristic frequency-depth (Lamouroux, 1998) and frequency-velocity (Lamouroux et al, 1995) relationships has been adopted in South Africa. Further research in testing of these models for recommending ecological flows for fish and macroinvertebrates is required.

In order to provide more accurate characterizations of the physical and hydraulic templates, and to improve the confidence in the environmental flow assessment on a comprehensive level of the Reserve determination, a three-dimensional spatial modelling approach as a suite of three modelling tools, QuickSurf, RiverCAD and HECRAS, has been proposed.

A framework for the hydraulic Reserve model, HERR, has been developed and is provided as an application of SPATSIM to address various requirements highlighted during Reserve assessments, including analysis of data, particularly for lower levels of determination where limited measured data are available, presentation of results and storage of hydraulic information generated in ecological Reserve determinations.

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